Monitoring the integrity of filament wound structures using built-in sensor networks

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ABSTRACT

Monitoring the integrity of filament wound composite structures such as solid rocket motors and liquid fuel bottles is important in order to prevent catastrophic failures and to prolong the service life of these structures. To ensure the safety and reliability of rocket components, they require frequent inspection for structural damages that might have occurred during manufacturing, transportation, and storage. The timely and accurate detection, characterization and monitoring of structural cracking, delamination, debonding and other types of damage is a major concern in the operational environment. Utilization of a sensor network system integrated with the structure itself can greatly reduce this inspection burden through fast in-situ data collection and processing. Acellent Technologies, Inc. is currently developing integrated structural monitoring tools for continuous monitoring of composite and metal structures on aircraft and spacecraft. Acellent's integrated structural monitoring system consists of a flexible sensor/actuator network layer called the SMART Layer, supporting diagnostic hardware, and data processing/analysis software. Recently, Acellent has been working with NASA Marshall Space Flight Center to develop ways of embedding the SMART Layer inside filament wound composite bottles. SMART Layers were designed and manufactured for the filament wound bottles and embedded in them during the filament winding process. Acellent has been working on developing a complete structural health monitoring system for the filament wound bottles including data processing tools to interpret the changes in sensor signal caused by changes in the structural condition or material property. A prototype of a filament wound composite bottle with an embedded sensor network has been fabricated and preliminary data analysis tools have been developed.

Keywords: Structural Health Monitoring; SMART Layer; SMART Suitcase; Built-in/Embedded sensors; Filament winding

1. INTRODUCTION

It is important to have up-to-date information on the integrity of structures in order to prevent catastrophic failures and to prolong their service life. This is especially true for rockets because of the cost and liability associated with each launch failure [1]. The problem is exacerbated by the fact that today's rockets heavily utilize composite material, which has a weight advantage but is prone to impact damages. To ensure the safety and reliability of rocket components, they require frequent inspection for accidental damages that might have occurred during manufacturing, transportation, and storage. Possible types of defect/damage in composite motor case and fuel bottles are matrix cracking, fiber breakage, delamination between plies, and debond between liner and composite overwrap [2]. Current approach of using conventional nondestructive evaluation (NDE) techniques such as C-scan, thermography, shearography, and eddy current, etc., is expensive, time-consuming, and often cannot be performed on structures already placed in service because of the inaccessibility or the special equipment required. Therefore, there is a need for a new diagnostic technique to perform in-situ examination of structural integrity in composite rocket motors.

Recently, the aerospace industry has started embracing the concept of Structure Health Monitoring [3], which uses sensors integrated permanently onto structures to monitor their condition throughout their lifetime. The types of sensors that are being used for this purpose include fiber-optic sensors, strain gauges, micro electromechanical sensors (MEMS), and piezoelectric sensors. Acellent Technologies' approach to structural health monitoring uses distributed miniature piezoelectric elements integrated onto structures to actively scan and diagnose the condition of a structure. Acellent uses

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the permanently integrated piezoelectric elements (either embedded or surface-mounted) as actuators and sensors to excite the structure and capture the corresponding structural response [4]. A piezo element is first used as an actuator to input a diagnostic stress wave. At the same time, the neighboring piezo elements are used as sensors to pick up the propagated signal. The captured signal is then examined by comparing it to the same signal captured at a previous time (i.e. the baseline). If a difference is observed, then a change in the structure's condition has occurred, indicating a possible damage in the area. By alternating all piezo elements on the structures as actuators and sensors, a diagnostic scan over the entire structure can be performed using all combinations of actuator-sensor paths. Previously, Acellent has applied this technique of active structural diagnostic using built-in piezo network to several different types of structures. The objective of the current investigation reported here is to apply Acellent's active structural diagnostic technique to composite rocket motor cases/fuel bottles, and demonstrate the technique's ability to perform in-situ structural inspection to locate damages on filament wound composite structures [5].

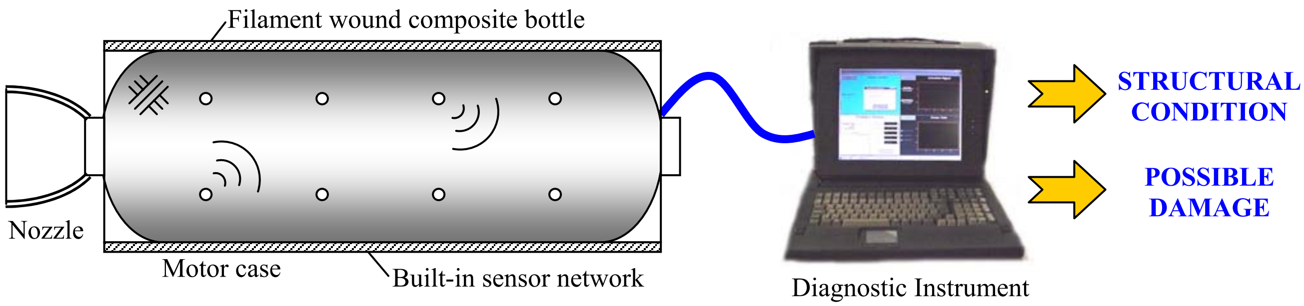

Figure 1: Concept of monitoring the integrity of filament wound composite structure using a built-in sensor network.

2. MANUFACTURING OF INSTRUMENTED BOTTLE

In order to instrument composite motor cases and fuel bottles with a built-in network of piezoceramic elements, Acellent's SMART Layer technique is utilized [6]. Up to now, the SMART Layer concept has been proven for several composite manufacturing techniques (including prepreg layup, wet layup, fiber placement, and resin transfer molding), but it has never been done for the filament winding process before. The filament winding process takes a bundle of composite fibers (a.k.a. a tow) and winds it over a cylindrical mandrel to build up successive layers of composite reinforcement. The challenges of incorporating SMART Layers inside a filament wound structure include the insertion and positioning of SMART Layers during the winding process, and the effect of non-uniform pressure applied by the narrow fiber tow on the SMART Layer during the winding process. All in all, many manufacturing issues have to be resolved in order to qualify the SMART Layer for use in the composite filament winding process.

2.1 Design of SMART Layer for filament wound bottle

For the composite filament winding process, the SMART Layers are designed in the shape of a thin flat strip with a row of piezoelectric elements (Figure 2). The piezo elements used are piezoceramic PZT that's 0.25 inch in diameter and 10 mils thick. There are 5 piezos on each SMART Layer strip. Because of the difference in geometry between the cylinder section and the dome section of the composite bottle, different piezo spacing were used on the SMART Layer strip. For the cylinder part the spacing is 5.5 inches, while in the dome part the spacing is 4.5 inches. Doing so provide a more uniform piezo grid array. To reduce electromagnetic EM noise, the SMART Layers are shielded on one-side with a half-mil (0.0005") thick solid copper foil. This produces an overall thickness of the layer of about 6 mils.

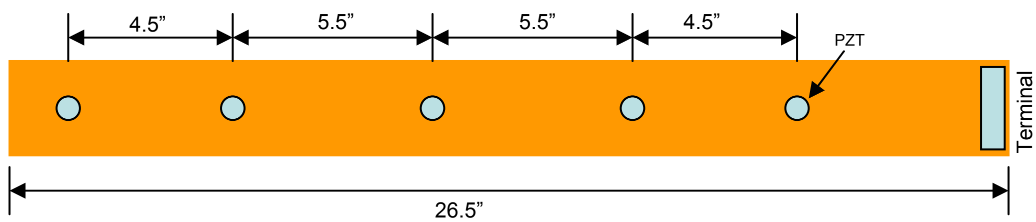

Figure 2: Design of the SMART Layer strip embedded in the bottle.

The composite bottle that is to be instrumented measures 20 inches long and 15 inches in diameter. For the preliminary design of the first bottle, eight SMART Layers strips are used (Figure 3), giving a sensor spacing of slightly less than 6 inches in the hoop direction. And since the sensor spacing in the axial direction is 5.5” in the cylindrical section, the resulting sensor grid is almost square in shape. In the dome section because the surface is curved in, the trapezoidal shape of the sensor grid is 4.5”, 5.5”, 5.5”, and 6.5” on the four sides.

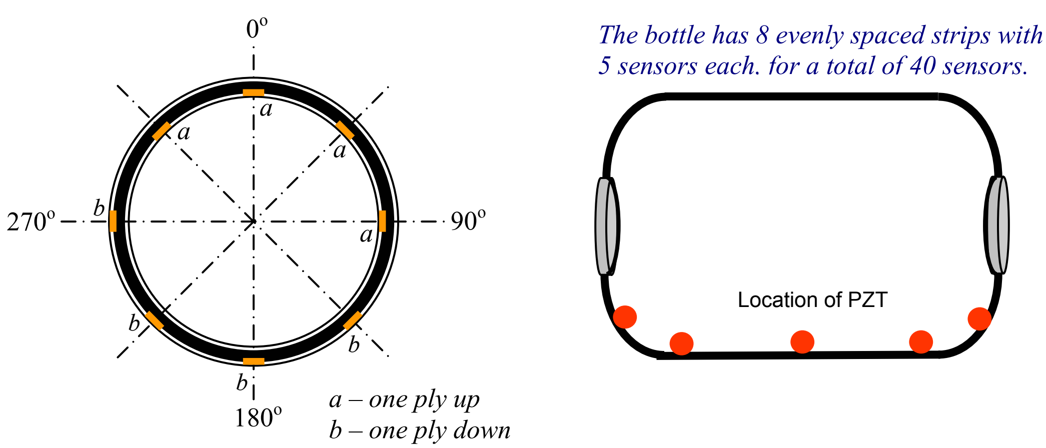

Figure 3: Location of SMART Layer strips and the distribution of sensors.

The design of the bottle has 5 hoop composite layers and 2 helical composite layers in the cylindrical section, but only two helical layers in the dome sections as illustrated in Figure 4. To determine the best location for embedding the SMART Layer strips, the eight strips are divided up and embedded at different depths. Because bending mode is the desired mode of structural excitation for our diagnostic purpose, the SMART Layer strips are placed as far away from the mid-plane of the bottle wall as possible [7]. Four SMART Layer strips are embedded one hoop layer above the aluminum liner, while the other four SMART Layer strips are embedded one hoop layer below the surface of the bottle. Because of this arrangement, two sensors on each “inner” strip are in contact with the aluminum bottle liner, while two sensors on each “outer” strip are exposed on the outer surface in the dome sections (Figure 4).

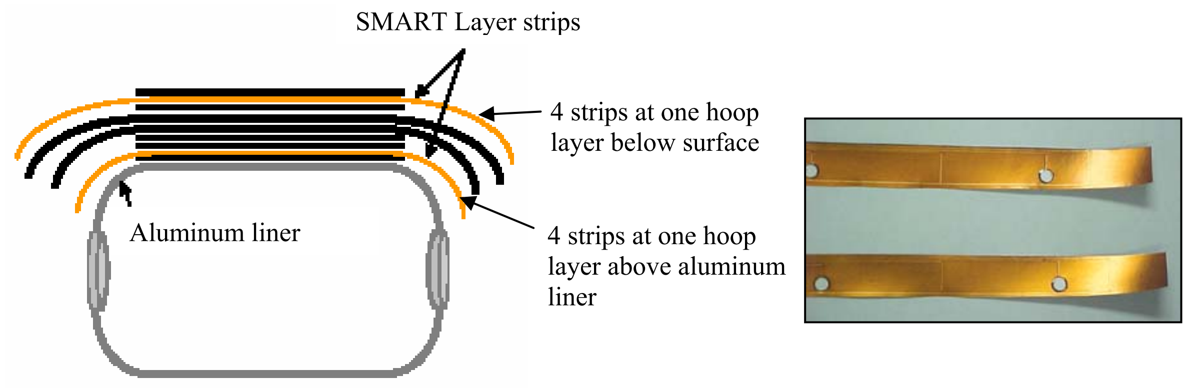

Figure 4: Embedding locations of SMART Layer strips in the filament wound bottle.

2.2 Fabrication of the bottle with SMART Layer

The fabrication of filament wound composite bottle was done at NASA Marshall Space Flight Center's facility. Some pictures showing the filament winding process that incorporates the SMART Layer strips into the bottle are shown in Figure 5. The main process involves winding composite prepreg tows onto an aluminum liner mandrel in either a hoop direction or a helical pattern. First, a hoop layer was wound onto the cylindrical section of the bottle. Four SMART Layer strips were then placed on top of the hoop layer and held in place by Teflon tape affixed on the dome part. Then two hoop layers were wound over the cylindrical section again. Next, the tapes used to fix the location of the four SMART Layer strips were removed before winding two helical layers over the entire bottle. Then, another hoop layer was wound over the cylindrical section. Next, the four outer SMART Layer strips were placed on the bottle, held in place by Teflon tape. Finally, a hoop layer was then wound on top of the cylindrical section, leaving the outer SMART Layer strips exposed on the dome part. All the piezo elements on the SMART Layer strips were oriented towards the thicker side of the composite: the piezos on the inner strips face outward and the piezos on the outer strips face inward. After the filament winding process, the composite bottle was cured at 350°F for 2 hours in an oven. Because the curing process did not use vacuum bagging, Teflon tape was used to hold the four outer SMART Layer strips onto the dome part of the bottle which was later removed after the cure.

Figure 5: Filament winding process incorporating the SMART Layer strips into the bottle.

2.3 Finished composite bottle with an embedded sensor network

Figure 6 shows the finished bottle and a thermographic scan image. The imager used is an Indigo Merlin running under Thermal Wave Imaging software (Width = 10, Gating = Exponential, 60Hz, 13mm lens). The heating source is a TWI Flash System, and for surface preparation the bottle was painted flat black [8]. From the thermographic image, the SMART Layer strips looked well bonded with the composite, except where the outer strips come out from under the composite on the dome part. This is due to the lack of external pressure applied during cure; holding it with tape does not appear to be good enough. Otherwise, the bottle looked good.

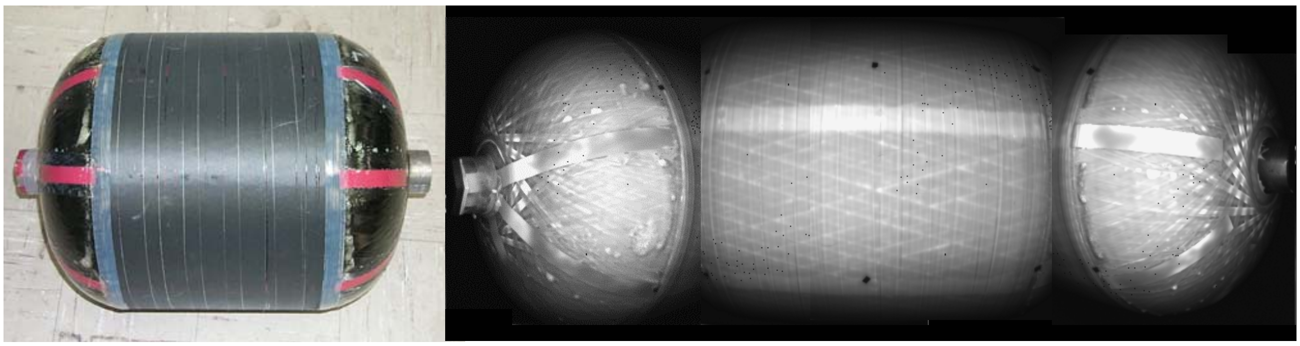

Figure 6: Finished bottle and thermographic image showing embedded SMART Layer strips.

3. SIGNALS AND INTERPRETATION

After the instrumented bottle had been fabricated, data were taken using the network of embedded piezoelectric actuators/sensors. The best propagation frequency that yielded the biggest signal was found to be between 35-65 kHz. Signals collected from the bottle turned out to be very strong, and were able to travel well beyond their neighboring sensors to even circle the entire circumference. The fact that signals can travel beyond the closest sensors is very useful – it allows the number of actuator-sensor paths to increase thus provides a better coverage over the area with finer resolution. It also provides redundancy coverage by having overlapping paths that can be used in case a sensor fails [9].

Comparing the signals from SMART Layer strips mounted at the two embedding locations (i.e. one near the outer surface and one near the inner surface), the signal strength at both locations are similar in the cylindrical section of the bottle. However, in the dome sections of the bottle, the inner strips produce stronger signals than the outer strips. This is due to the fact that the inner strips are wound inside a helical composite layer in the dome sections, while the outer strips are simply exposed on the surface. Because of this, the better location for placing the SMART Layer strips turns out to be the one near the inner surface for this particular bottle design.

After a set of baseline data had been collected from all paths on the bottle, damage was introduced onto the bottle to look at its effect on the sensor signals [10]. To introduce impact damage, a ball-peen hammer was held in contact with the bottle to serve as an impactor tip, and then an 8-lb 3-ft long sledgehammer was swung to strike the top of the ball-peen hammer (Figure 7). Because this type of composite-wrapped bottles take a lot of impact force/energy to get any damage, the impact process was repeated several times until a damage was visible on the surface. The size of the resulting damage on the surface was approximately half an inch in diameter.

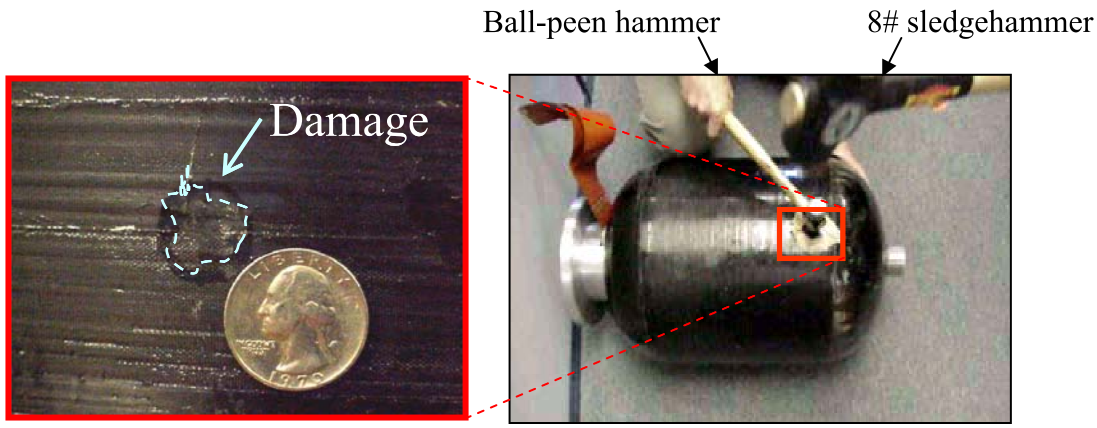

Figure 7: Damage test by using hammer impact to create damage.

Figure 8 shows the comparison of a sensor signal before and after damage. For illustration purpose, the signal is taken from an actuator-sensor path that passes near the damage site and therefore is affected significantly. An enlargement of the plot shows that after the structure had been damaged, the signal amplitude becomes weaker and is shifted [11]. To quantify the change in the signal due to this damage, the post-damage signal can be subtracted from the original (baseline) signal before there was damage. The remaining difference is called a scatter signal that is used to quantify the amount of change in the signal of a particular actuator-sensor path.

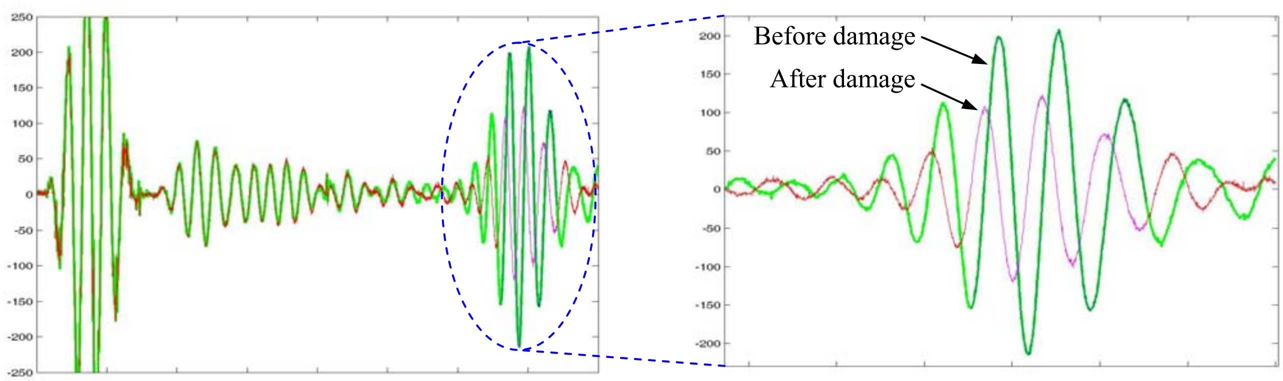

Figure 8: Example of the signal collected by a built-in sensor before and after there is damage in the structure.

The scatter signals from all different paths on the bottle can be displayed together to produce a comprehensive image to show their relative magnitude. Since different paths have different propagation distance, and that signal amplitude is a function of distance, this factor has to be taken out in order to make the signals from different paths directly comparable. To do so, the signals from all paths are first normalized using their respective distance so that all paths show similar signal amplitude no matter how long the actuator-sensor path is. After the factor of distance has been taken out by normalizing the data, the scatter signal amplitude of each path is plotted as a color gradient contour on the bottle. The

result of the combined plot showing the scatter signal amplitudes from all paths is shown in Figure 9. Where multiple paths are affected by the impact damage that results in prominent scatter signals, their effects are added up to show a heighten intensity that's used to indicate the presence of damage. This display technique can be used as a fast imaging method to help visualize the approximate location and extent of an impact damage.

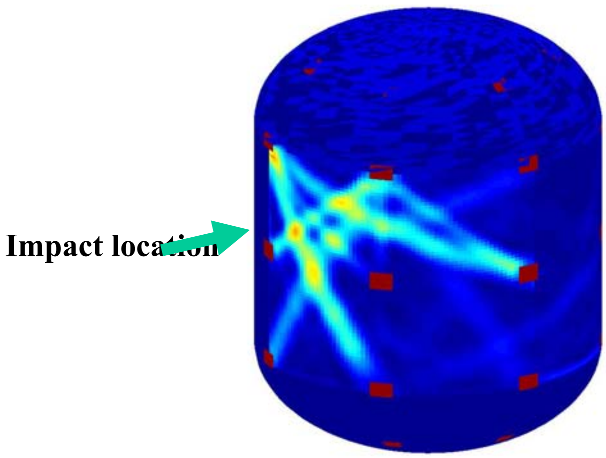

Figure 9: Damage identification result using signals collected by a network of built-in sensors.

4. ON-GOING WORK

In the coming weeks, four more bottles with embedded SMART Layer strips will be fabricated at NASA's Marshall Space Flight Center facility. The design will be improved based on our findings reported here. Specifically, the number of SMART Layer strips will be reduced from 8 to 6, since sensor signals appear to be strong and travel well on this bottle structure. This will reduce the number of sensors that are used to cover the bottle to 30, which is exactly the number of channels available on our SMART Suitcase [4], therefore allowing the whole bottle to be scanned at one time. In the new design, the SMART Layer strips will be embedded at the inner surface between the aluminum liner and the first helical composite ply. The reason for this choice is because the strips at this location appear to bond better than the ones near the outer surface, and that they provide stronger signals.

After the four bottles are fabricated, some of them will be tested under usage condition. The type of tests that may be done include cryogenic test and pressurization test. In the cryogenic test, the instrumented bottles can be filled with a liquid cryogen to simulate the operating condition. The sensors will then be examined at the cryogenic temperature to measure their performance. In the pressurization test, the instrumented bottles can be loaded up to near the burst pressure to test the survivability of the sensors and measure their performance in collecting information from the structure up to failure. Further impact tests will also be performed on the bottles, and the damaged bottles will likely be sent back to NASA for a C-scan or thermography so the result can be used to further improve the technique for visualization of signals from a network of embedded sensors.

5. SUMMARY

To ensure safe and reliable operation of rockets, they require frequent inspection for possible structural damages that could lead to catastrophic launch failures. A technique is being developed to monitor the integrity of filament wound structures such as composite rocket motor cases and fuel bottles using a network of built-in piezoceramic transducers. The technique utilizes Acellent Technologies' SMART Layer concept to integrate a network of piezoceramic

transducers onto a composite bottle during the filament winding process. The first prototype of the instrumented bottle has been fabricated successfully at NASA's Marshall Space Flight Center facility, and the SMART Layer approach has been shown to be compatible with the composite filament winding process. Embedding SMART Layer strips inside bottles by wrapping prepreg tows over them has been found to provide good bonding to the liner and the composite, as shown by a post manufacture thermography scan. Signals recorded from the prototype bottle were found to be exceptionally strong such that they can travel the entire circumference of the bottle, which allows the design of future bottles to have even fewer sensors. Comparison of signal strength between SMART strips mounted at the two embedding locations showed that inner strips produce stronger signal than outer strips, therefore the inner surface location is a better choice for the placement of SMART strips inside this bottle. Preliminary impact tests have been performed on the prototype bottle, and a scan of the bottle using the developed software algorithms was able to locate the damage. Further signal processing and imaging techniques are being developed to improve the display of the impact damage.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

1. L.C. Gunn III, "Operational Experience with Health Monitoring on the Delta II Program," *Proceedings of the 2nd International Workshop on Structural Health Monitoring*, Stanford, CA, September 8-10, 1999.
2. *Proceeding of the Graphite/Epoxy Rocket Motor Case Experience Sharing Meeting.* Air Force Material Command, Space and Missile Systems Center, Launch Vehicles Program Office, Delta II Program. May 5-7, 1998.
3. R. Ikegami, "Structural Health Monitoring: Assessment of Aircraft Customer Needs," *Proceedings of the 2nd International Workshop on Structural Health Monitoring*, Stanford, CA, September 8-10, 1999.
4. M. Lin, X. Qing, A. Kumar, and S. Beard, "SMART Layer and SMART Suitcase for Structural Health Monitoring Applications," *Proceedings of SPIE Smart Structures and Materials Conference,* Vol.4332, p.98-106, March 2001.
5. S. Beard and A. Kumar, "Development of Intelligent Composite Using Integrated SMART Layer Technology," *Progress Report to the Space and Missile Defense Command* for Contract No. DASG60-01-C-0064, 2001.
6. M. Lin and F.K. Chang, "Design and Fabrication of Built-in Diagnostic for Composite Structures," *Proceedings of the 12th American Society of Composites Technical Conference*, Baltimore, MD, 1998.
7. R.S. Roh and F.K. Chang, "Effect of Impact Damage on Lamb Wave Propagation in Laminated Composites," *ASME-AD,* Vol. 46, pp. 127-138, 1995.
8. S. Russell, J. Walker, and G. Workman, "Efficient Nondestructive Evaluation of Prototype Carbon Fiber Reinforced Structures," *Proceedings of the 10th US-Japan Conference on Composite Materials*, Stanford, September 16-18, 2002.
9. S. Beard and F.K. Chang, "Active Damage Detection in Filament Wound Composite Tubes Using Built-in Sensors and Actuators," *J. of Intelligent Material Systems and Structures*, Vol. 8, No. 10, 1997, pp. 891-898.
10. K. Choi, C. Keilers Jr. and F.K. Chang, "Impact Damage Detection in Composite Structures Using Distributed Piezoceramics," *Proceedings of the 35th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Part I, 94-1322, pp. 118-124, 1994.
11. C.H. Keilers Jr. and F.K. Chang, "Damage Detection and Diagnosis of Composites Using Built-in Piezoceramics," *Proceedings of SPIE on Smart Structures and Material Systems*, Vol. 1917, pp. 1009-1019, 1993.